Errors in heat flux measurements due to the thermal resistance of heat flux disks

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DUCHARME, MICHEL B., JOHN FRIM, AND PETER TIKUISIS. *Errors in heat flux measurements due to the thermal resistance of heat flux disks.* J. Appl. Physiol. 69(2): 776–784, 1990.—Questions have been raised regarding the effect of the thermal resistance of heat flux tranducers (HFTs) on the thermal flux from the skin. A model capable of simulating a large range of "tissue" insulation (variable-R model) was used to study the effect of the underlying tissue insulation on the relative error in heat flux due to the thermal resistance of the HFTs. The data show that the deviation from the true value of heat flux increases as the insulation of the underlying tissue decreases ($r = 0.99$, $P < 0.001$). The underestimation of the heat flux through the skin measured by an HFT is minimal when the device is used on vasoconstricted skin in cool subjects (3–13% error) but becomes important when used during vasodilation in warm subjects (29–35% error) and even more important on metallic-skin mannequins (>60% error).

heat flux transducer; tissue insulation

THE DIRECT ASSESSMENT of heat flux from the body is a basic measurement in thermal physiology. Heat flux transducers (HFTs) are being increasingly used for this purpose in preference to calorimeters because of their reduced cost, ease of application, and capability to be used under different and often more realistic environmental conditions.

An HFT consists of a sensitive thermopile composed of many fine-gauge thermocouples connected in series on opposite sides of a flat matrix with a stable thermal resistance. This thermal resistance creates a temperature difference across the matrix in the presence of heat flux

$$\Delta T = R_T \cdot \dot{H} \qquad (1)$$

where ΔT is temperature difference, R_T is thermal resistance, and $\dot{H}$ is heat flux.

The temperature difference is detected by the thermocouple junctions, and the voltage generated across the thermopile is proportional to the heat flux through the HFT. The sensitivity of the device ($mV \cdot m^2 \cdot W^{-1}$) is proportional to the number of thermocouple junctions in series and to the thermal resistance of the matrix.

Despite the simplicity of the design, questions have been raised regarding the reliability and accuracy of the HFTs. Nuckols and Piantadosi (6) developed a calibration technique for HFTs and showed an effect of temperature on the performance of the HFTs as well as significant differences of up to 20% between the factory-supplied calibration constants and those determined experimentally. The authors concluded that potentially large errors in calculated heat flux may arise if transducers are not accurately calibrated. They suggested that careful recalibration of the disks should be made to avoid this error.

In contrast, Sowood (14) showed, by a similar but distinct method of calibration and a different brand of HFT, that the experimentally determined calibration constants of HFTs were the same as those of the manufacturer minus $\sim 6\ W \cdot m^{-2} \cdot mV^{-1}$. He concluded that the differences between the two sets of values were negligible and that the devices could be used without recalibration.

These two studies raise questions regarding a potential difference in the accuracy of HFT calibration between manufacturers. If such a difference exists, it can be demonstrated by a single reliable method of calibration for both types of HFTs. In the present study, two brands of HFTs that have characteristics similar to those used by Nuckols and Piantadosi (6) and Sowood (14) were recalibrated to determine whether the different observations obtained by those previous studies were due to a difference in the accuracy of the manufacturers' calibrations or attributed to the different methods of calibration used by the authors.

Poppendick (8), Gin et al. (5), and later Wissler and Ketch (16) observed another potential source of error involved in the use of HFTs. An HFT inherently introduces a reactive error when used to measure the heat flux of any material attached to it. The addition of the thermal resistance of the HFT on the material surface will add to the insulation of the region and consequently change the temperature and heat flux at the surface. When an HFT is used on the skin in water, where the thermal resistance between the skin surface and the environment is small, a significant local increase in resistance may occur. Therefore, the voltage obtained from the HFT is only representative of the heat flux from the

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tissue immediately below the disk, not that from the adjacent areas of exposed skin. Wissler and Ketch (16) estimated in their study that, when used in water, the HFT can underestimate the heat flux by 15–20% because of the thermal resistance of the transducer. In addition, Gin et al. (5) and Wissler and Ketch (16) suggested that the error could be even more important when HFTs are used on vasodilated skin. Despite the suggestion that the magnitude of the error might be related to the vascular state of the underlying tissue, no information is available in the literature about the relationship between the error in heat flux values due to the thermal resistance of HFTs and the underlying tissue insulation during water immersion.

In addition to the recalibration, this study will quantify, through theoretical considerations and observations from a model and from human subjects, the magnitude of error involved in heat flux measurements when HFTs are used on exposed tissues of various vasomotor states during water immersions.

MATERIALS AND METHODS

Calibration of HFTs. HFTs from two different manufacturers (*manufacturers A* and *B*) with similar characteristics (disk of 2.5 × 0.2 cm, waterproofed, sensitivity ranging from 8 to 15 $\mu V \cdot m^2 \cdot W^{-1}$) were recalibrated with an adaptation of the method described by Nuckols and Piantadosi (6). These two types of HFT disks were chosen for evaluation because they offer the best potential for the measurement of heat flux in a variety of environments.

The HFTs were checked for their calibration by the Rapid-k instrument (Dynatech, Cambridge, MA), an apparatus designed to determine the thermal conductivity value of materials in accordance with American Society for Testing of Materials C518 Specifications for the Measurement of Thermal Conductivity by Means of the Heat Flow Meter. To ensure optimal performance of the Rapid-k, the heat flux meter of the instrument was calibrated against two thermal resistance standards borrowed from the Thermal Performance Section of the National Research Council of Canada (MDGF Transfer Standard no. 357-172-A and B).

During the calibration tests, the HFTs were held firmly within a test bed (made with Teflon and hardboard) in the central area of the test section of the Rapid-k (effective area), where the thermal flux is one-directional between the hot and cold plates (Fig. 1). A test bed was used to *1*) create a range of heat flux through the HFTs similar to that expected from the body under different environmental conditions (0–500 W/m^2); *2*) optimize the homogeneity of heat flux around the HFTs because the value of thermal conductivity (k) for the Teflon [0.24 $W \cdot °C^{-1} \cdot m^{-1}$ (1)] is close to the k value of the HFTs (between 0.20 and 0.30 $W \cdot °C^{-1} \cdot m^{-1}$ according to the type of HFT); and *3*) ensure good surface contact with the HFTs. To optimize the heat transfer from the test-bed matrix to the HFTs, the interfaces were filled with a thermally conductive grease (Wakefield Engineering, Wakefield, MA). Finally, the HFTs were fixed to the HFT support with the same kind of tape used to fix the HFTs over the skin (Blenderm surgical tape, 3M). Figure 1*B* presents the complete test setup of the system within the effective area of the test section of the Rapid-k as used during a calibration run.

During the calibrations, the transducers were exposed

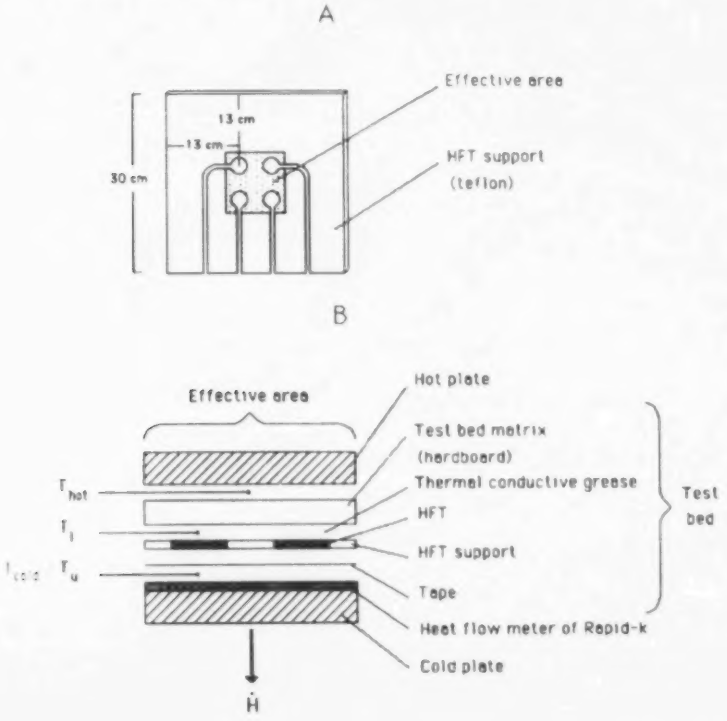

FIG. 1. *A*: representation of HFT support used for calibration of HFTs. Four HFTs were positioned within HFT support in effective area (embedded in holes of support). *B*: representation of effective area of test section for calibration and determination of k value of HFTs. T_{hot}, T_{cold}, T_l, and T_u represent location of different thermocouples.

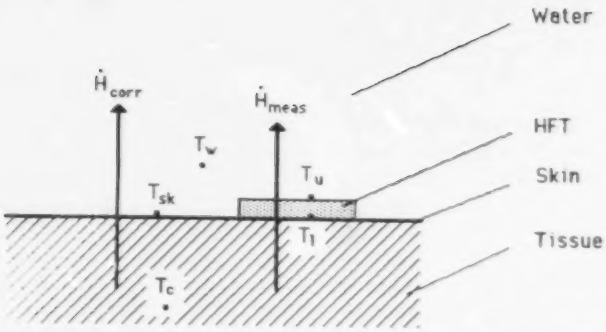

FIG. 2. Schematic representation of thermal system involved in demonstration of theoretical equivalence of equations proposed by different authors for correction for R_T.

to heat flux ranging from 0 to 500 W/m^2 by the temperature of the hot plate varying from 30 to 95°C. The temperature of the cold plate was maintained constant at ~30°C to minimize the possible effect of temperature on HFT responses and to avoid the change in k value of the HFTs with temperature. Only values obtained during thermal steady state were used to calculate the calibration constant. Thermal equilibrium was considered established when the ratio of monitored heat flux from the Rapid-k ($\dot{H}_{Rapid\text{-}k}$) over the temperature differential (difference between hot and cold) did not change by >1% over a 20-min period. The calculation of the HFT calibration constant was made by transforming the voltage output of the Rapid-k heat flow meter into heat flux by use of the previously established calibration curve of the Rapid-k and the voltage output of the HFT (mV) under investigation as

$$\text{calibration constant} = \frac{\dot{H}_{Rapid\text{-}k}}{V} \qquad (2)$$

where V is voltage output and the calibration constants are in $W \cdot m^{-2} \cdot mV^{-1}$.

The reproducibility of the calibration method was verified by the recalibration of four HFTs over a 2-wk period. Verification of the consistency of our calibration method was obtained with a double-layer HFT test. This test consisted of measuring the value of heat flux that passed through two superimposed HFTs sandwiched between two pieces of Teflon. Because the heat flux is the same through the two HFTs, the calculated values of heat flux by use of the calibration constant determined by the Rapid-k and the signal output of each HFT, should be equal if the calibration method is consistent.

Determination of the HFT thermal conductivity. The determination of the thermal conductivity value for the HFTs was performed at the same time as the calibration tests (Fig. 1). For each HFT on the bed test, two fine-gauge thermocouples (40 gauge) calibrated against a quartz thermometer (Hewlett Packard 2804A) to an accuracy of 0.06°C were fixed on the opposite surfaces of the transducer. The k values of HFTs were calculated with the Fourier linear heat flow equation (10)

$$k = \frac{\dot{H}_{Rapid\text{-}k} \cdot x}{T_l - T_u} \qquad (3)$$

where k is the thermal conductivity of the HFT and the tape in $W \cdot °C^{-1} \cdot m^{-1}$, x is the thickness of the HFT plus the tape in m, and $T_l - T_u$ is the temperature difference

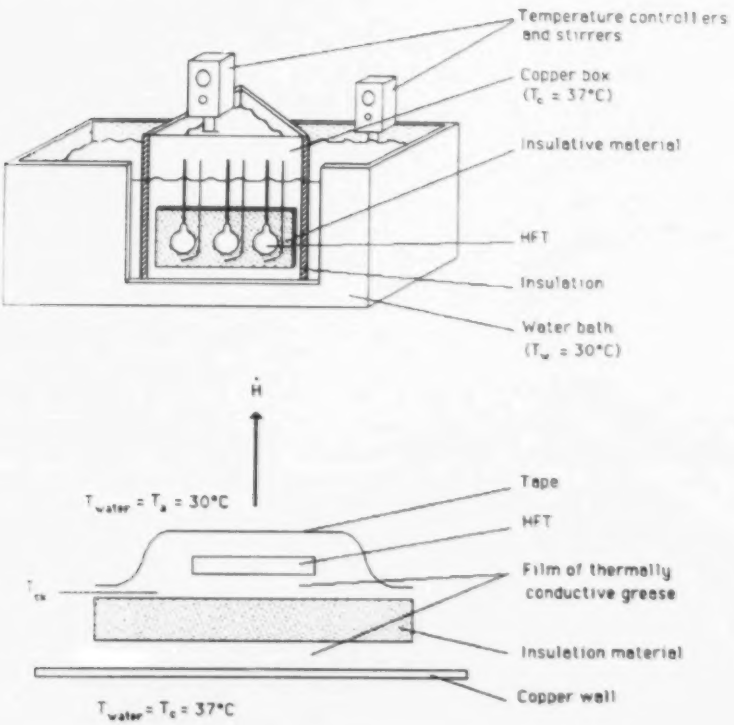

FIG. 3. Variable-R model used for study of relationship between underlying tissue insulation and relative error in heat flux due to R_T. Thermal insulation of model wall (copper box) was varied by use of different insulative material and thickness.

between the two opposite surfaces of the HFT including the tape in °C (Figs. 1 and 2). The tape is included in the calculation of the k value because it contributes to the insulation of the HFT when used to fix the transducer on the skin.

Variable-resistance model. To determine the relationship between the underlying tissue insulation and the relative error in thermal flux due to the thermal resistance of HFTs, a model system was developed to simulate a large range of "tissue" insulation values (Fig. 3). The variable-resistance (R) model consisted of an insulated water-filled copper box (maintained at 37°C with a proportional temperature controller) immersed in a water bath maintained at 30°C with a second proportional temperature controller. The thermal insulation of the model was varied by changing the material type (polystyrene, neoprene, hardwood, aluminum, and copper) and thickness (1–13 mm) on one wall to give insulation values ranging from 2.7×10^{-4} to 4.4×10^{-1}°C·m^2·W^{-1}. For each setting, the thermal flux through the system was measured with three recalibrated HFTs from each manufacturer fixed on the external surface of the insulation with Blenderm surgical tape. The interfaces between the copper wall of the variable-R model and the insulative material and between the insulative material and the HFT were filled with thermally conductive grease. The different surface temperatures were measured with fine calibrated type T thermocouples (40 gauge). The thermal insulation of the model (RM) was calculated as

$$RM = \frac{T_c - T_{sk}}{\dot{H}_{corr}} \tag{4}$$

where $\dot{H}_{corr}$ is the thermal flux (W/m^2) through the wall of the model corrected for the insulating effect of the HFT, T_c is the "core" temperature of the model (37°C), and T_{sk} is the "skin" temperature of the model. The thermal insulation values were calculated with the mean values of thermal flux and temperature recorded during the last 10 min of each experiment, when thermal stability was achieved.

Theory of measurement error for the thermal resistance of heat flux disks. Various correction formulas applicable for both air (see APPENDIX) and water exposure are available in the literature to calculate $\dot{H}_{corr}$. Figure 2 illustrates the physical system involved in the demonstration of the theoretical equivalence of the equations proposed by different authors for the calculation of $\dot{H}_{corr}$. At steady state, Fourier's law of heat transfer through the region adjacent to the HFT leads to the equation

$$\dot{H}_{corr} = \frac{(T_c - T_{sk})}{RM} \tag{5}$$

$$= \frac{(T_{sk} - T_w)}{R_w} \tag{6}$$

$$= \frac{(T_c - T_w)}{(RM + R_w)} \tag{7}$$

where T_w is the water temperature and R_w is the thermal resistance of the water. For the region underlying the HFT

$$\dot{H}_{meas} = \frac{(T_c - T_l)}{RM} \tag{8}$$

$$= \frac{(T_l - T_u)}{R_T} \tag{9}$$

$$= \frac{(T_u - T_w)}{R_w} \tag{10}$$

$$= \frac{(T_c - T_w)}{(RM + R_T + R_w)} \tag{11}$$

where $\dot{H}_{meas}$ is the measured flux value affected by the thermal resistance of the HFT, T_l and T_u are the temperatures on the lower and upper sides of the HFT, respectively, and R_T is the thermal resistance of the transducer.

By substituting *Eq. 8* into *Eq. 5*

$$\dot{H}_{corr} = \frac{(T_c - T_{sk})\dot{H}_{meas}}{(T_c - T_l)} \tag{12}$$

which is the correction formula proposed by Gin et al. (6). Alternatively, from *Eqs. 9* and *10*

$$R_w = \frac{(T_l - R_T \cdot \dot{H}_{meas} - T_w)}{\dot{H}_{meas}} \tag{13}$$

After substitution of *Eq. 13* into *Eq. 6* and some rearrangement

$$\dot{H}_{corr} = \frac{(T_{sk} - T_w)\dot{H}_{meas}}{(T_l - T_w) - R_T \cdot \dot{H}_{meas}} \tag{14}$$

which is the correction formula proposed by Strong et al. (15) (the original equation derived by Strong et al. is mistyped). The correction formulas *Eqs. 12* and *14* are both sensitive to small differences between T_{sk} and T_u. Small errors (as low as 0.05°C) in the measurement of these temperatures can lead to wide-ranging values of $\dot{H}_{corr}$.

A more appropriate correction formula is one that avoids the temperatures T_l and T_u and can be obtained as follows. Substitution of *Eq. 11* into *Eq. 7* leads to

$$(RM + R_w)\dot{H}_{corr} = (RM + R_w)\dot{H}_{meas} + R_T \cdot \dot{H}_{meas} \tag{15}$$

which on rearrangement becomes

$$\dot{H}_{corr} = \frac{(RM + R_w)\dot{H}_{corr} \cdot \dot{H}_{meas}}{(RM + R_w)\dot{H}_{corr} - R_T \cdot \dot{H}_{meas}} \tag{16}$$

After substitution of *Eq. 7* into *Eq. 16* and some rearrangement

$$\dot{H}_{corr} = \frac{\dot{H}_{meas}}{1 - R_T \cdot \dot{H}_{meas}/(T_c - T_w)} \tag{17}$$

which is the correction formula derived by Wissler and Ketch (16) and later by Sowood (14). The Wissler-Ketch correction is the most appropriate to calculate $\dot{H}_{corr}$ because it is the least sensitive to error in temperature measurements.

To obtain a relationship between the relative size of

the correction and the relative thermal resistance of the HFT to the model, first *Eq. 17* can be rearranged so that

$$\frac{\dot{H}_{corr}}{\dot{H}_{meas}}\left(1 - \frac{R_T \cdot \dot{H}_{meas}}{T_c - T_w}\right) = 1 \qquad (18)$$

which becomes

$$\frac{\dot{H}_{corr}}{\dot{H}_{meas}} = 1 + \frac{R_T \cdot \dot{H}_{corr}}{T_c - T_w} \qquad (19)$$

$$= 1 + \frac{R_T \cdot \dot{H}_{corr}(T_c - T_{sk})}{(T_c - T_w)(T_c - T_{sk})} \qquad (20)$$

and on substitution of *Eq. 7* becomes

$$\frac{\dot{H}_{corr}}{\dot{H}_{meas}} = 1 + \frac{R_T}{R_M}\left(\frac{T_c - T_{sk}}{T_c - T_w}\right) \qquad (21)$$

which is a convenient form to make certain predictions on the relative size of the correction based on the relative thermal resistance of the HFT to the model. First, if R_T is small compared with R_M, such as a state of vasoconstriction in human tissue during cold stress, then the correction is also small. This is especially true for cold water immersion, where T_c may be several degrees higher than T_{sk} and T_{sk} is only slightly higher than T_w. Second, if the underlying model is human tissue in a state of vasodilatation so that R_M and the difference between T_c and T_{sk} are reduced, then the correction becomes important, more for water immersion, where the difference between T_c and T_w is less than for air exposure. Third, if R_T is large compared with R_M, such as with a metallic mannequin, then the correction becomes quite important. These predictions will be examined experimentally and discussed more completely further on.

Tests with human forearms immersed in water. The objective of these tests was to illustrate and complement the theory and variable-R model results with experimental data from immersions of human forearms exposed at different T_w. The methods used during the study were approved by the Institutional Human Ethics Committees. The experiments involved 10 healthy male subjects between 18 and 30 yr of age. Each experiment consisted of immersing the forearm in a water bath for 3 h at a constant temperature between 15 and 36°C. These T_w were chosen to create a large range of tissue insulation. Each subject experienced two different randomly chosen temperatures, one for each forearm, separated by 1 wk. During the experiments, the subjects were in a sitting position, and the ambient temperature of the room was 25 ± 1°C.

The tissue temperature was continuously monitored during the immersions at each 5 mm of tissue from the forearm axis (determined from computed tomography scanning) to the skin on the proximal third of the forearm (superficial muscle: flexor carpi ulnaris, deep muscle: flexor digitorum profundus). The temperature of the muscle was recorded with a fine calibrated multicouple probe implanted under local anesthesia (skin refrigerant, ethyl chloride, Graham-Field) by a method detailed elsewhere (4). The temperature values were corrected for the thermal conductivity effect along the wires of the probe (4). The maximal value of tissue temperature, always found at the longitudinal axis of the forearm, was used to represent the core temperature of the segment.

The heat flux at the skin of the forearm was measured with a recalibrated HFT, and the skin temperature was measured with a fine calibrated 40-gauge thermocouple probe. Both the HFT and the thermocouple were fixed a few millimeters away from the site of the muscle temperature measurements with Blenderm surgical tape. Thermally conductive grease was applied underneath the HFT to optimize the heat transfer between the skin and the transducer. The $\dot{H}_{corr}$ values were calculated by use of the Wissler-Ketch correction previously described (*Eq. 17*). All thermal flux and temperature values used in the calculation were from the last 15 min of each experiment, when thermal stability was achieved.

Statistical analyses. The different linear and curvilinear regression analyses and independent *t* tests presented throughout this study were performed with statistical programs (Biomedical Computer Programs, BMDP, Los Angeles, CA). The values are expressed as means ± SD.

RESULTS

Calibration of HFTs. All HFTs from both manufacturers showed linear responses over the calibration heat flux range of 0–500 W/m. The correlation between the HFT voltage output and the $H_{Rapid\text{-}k}$ is highly significant ($P < 0.001$) for each HFT calibrated. Each transducer response had a different slope, but the linearity of the responses and the nearly zero intercepts supported the use of a constant calibration factor for each transducer over the test range of heat flux.

The calibration constants for 15 HFTs from *manufacturer A* (HFTs *A*) and 12 HFTs from *manufacturer B* (HFTs *B*) determined by the Rapid-k instrument and those provided by the manufacturers are presented in Table 1. The mean difference between our calibration constants and the manufacturer's constants is 20.2 ± 7.1% (8.3–32.2%) for the HFTs *A* and −0.7 ± 4.8% (−8.6–8.8%) for HFTs *B* (4.0 ± 2.5% in absolute value). The mean difference is significantly different from zero for the HFTs *A* ($P < 0.001$) but not for the HFTs *B*. The mean differences are significantly different from each other ($P < 0.001$). The repeat calibrations of four HFTs over a 2-wk period gave a mean variability of <2% from the first determination, which confirms the reproducibility of the calibration technique. In addition, the calculated heat flux values from two superimposed HFTs, by use of the respective calibration constants and voltage outputs, gave for three tests a mean difference between the two values of <2%. These results confirmed the consistency of the calibration between HFTs.

Value of k of HFTs. The mean value of *k* of the HFTs at 30°C determined by the Rapid-k is 0.194 ± 0.018 $W \cdot °C^{-1} \cdot m^{-1}$ ($n = 27$) for HFTs *A* and 0.316 ± 0.015 $W \cdot °C^{-1} \cdot m^{-1}$ ($n = 24$) for HFTs *B*. The two values are significantly different ($P < 0.001$) and specific to the characteristics of fabrication of each type of HFT. The mean difference between the *k* value determined by the Rapid-k and that supplied by the manufacturer is 16.0% for the HFTs *A* (manufacturer $k = 0.225\ W \cdot °C^{-1} \cdot m^{-1}$)

TABLE 1. *Thermal constants for HFTs A and HFTs B*

Serial No.	Thermal Constant, $W \cdot m^{-2} \cdot mV^{-1}$		%Deviation
	Manufacturer	Recalibration	
	HFTs A		
1549	64.7	55.32	17.0
1550	69.4	56.36	23.1
1551	71.0	62.46	13.7
1552	69.4	58.56	18.5
1553	71.0	57.91	22.6
1554	69.4	57.36	21.0
1558	69.4	62.43	11.2
1559	72.5	66.93	8.3
1560	72.5	62.90	15.3
1561	80.4	61.54	30.7
1562	94.6	77.52	22.0
1563	71.0	60.96	16.5
1564	74.1	56.46	31.3
1565	93.0	70.33	32.2
1566	72.5	60.90	19.1
Means ± SD			20.2±7.1
	HFTs B		
1118	111.04	116.76	−4.9
1122	123.66	120.21	2.9
1123	123.66	126.82	−2.5
1120	123.66	121.86	1.5
1119	118.29	123.10	−3.9
1115	117.03	128.00	−8.6
1121	120.82	123.25	−2.0
1116	118.29	122.68	−3.6
1172	124.35	127.56	−2.5
1173	119.00	113.25	5.1
1175	114.20	112.36	1.6
1176	114.20	104.29	8.8
Means ± SD			−0.7±4.8

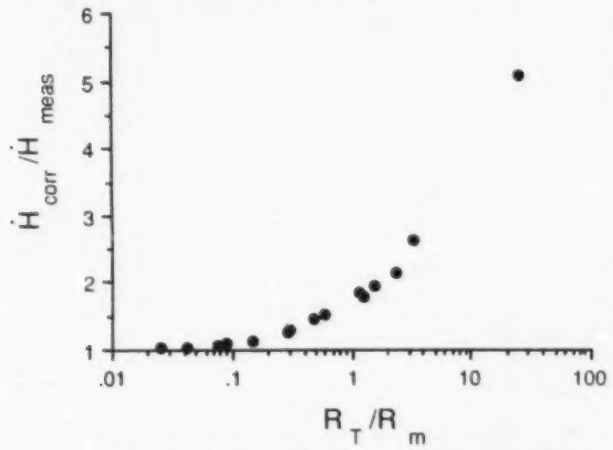

FIG. 4. Relationship between $\dot{H}_{corr}/\dot{H}_{meas}$, which represents relative error in measured thermal flux due to R_T, and R_T/RM for all values of RM studied. The same relationship is valid for both types of HFT.

and 46.0% for HFTs *B* (manufacturer $k = 0.462\ W \cdot °C^{-1} \cdot m^{-1}$).

Variable-R model. Eight experiments that used three HFTs *A* and seven experiments that used three HFTs *B* were performed by use of the variable-R model to establish the relationship between the underlying "tissue"

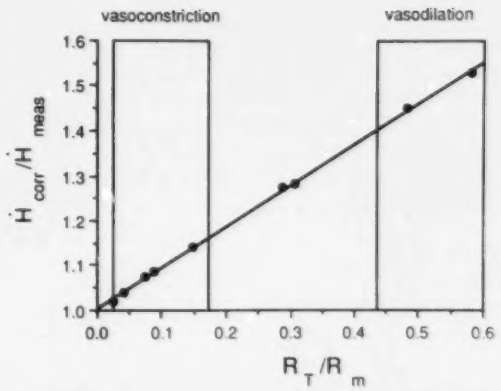

FIG. 5. Relationship between $\dot{H}_{corr}/\dot{H}_{meas}$, which represents relative error in measured thermal flux due to R_T, and R_T/RM for physiological range of RM studied. The same relationship is valid for both types of HFT.

TABLE 2. *Temperature and heat flux data for last 15 min of a 3-h immersion of forearm in water at different temperatures*

	T_w, °C			
	15.0	20.0	30.0	36.0
T_{re}, °C	37.4±0.3	37.5±0.3	37.5±0.2	37.4±0.3
T_{cs}, °C	24.5±3.0	27.8±1.8	34.3±0.5	36.8±0.2
T_{sk}, °C	15.2±0.1	20.2±0.1	30.1±0.1	36.1±0.1
$\dot{H}_{meas}$, W/m²	83.1±7.2	67.7±10.2	43.2±7.4	22.9±7.1
$\dot{H}_{corr}$, W/m²	90.5±7.7	74.0±10.6	48.6±8.6	31.7±12.1
%Dev	8.2±0.7	8.5±2.9	10.9±0.8	25.3±7.0

Values are means ± SE. T_{re}, rectal temperature of the subject; %Dev, percentage of deviation between $\dot{H}_{meas}$ and $\dot{H}_{corr}$. T_{sk} was measured with a fine-gauge thermocouple.

insulation and the relative error in thermal flux due to R_T. Figure 4 presents the relationship between the relative error ($\dot{H}_{corr}/\dot{H}_{meas}$) and the relative insulation of the HFT to the underlying model (R_T/RM) for all the range of RM studied. It is important to remember that the values of $\dot{H}_{corr}$ were not measured but were derived from the theory by the Wissler and Ketch correction formula (*Eq. 17*). No significant difference exists between the relationship determined for each type of HFT. A curvilinear relationship can be described for both types of HFTs by

$$\frac{\dot{H}_{corr}}{\dot{H}_{meas}} = 1.721 + 1.145 \log \frac{R_T}{RM} + 0.688\left(\log \frac{R_T}{RM}\right)^2 + 0.156\left(\log \frac{R_T}{RM}\right)^3 \qquad r^2 = 0.998 \qquad (22)$$

When only the physiological range for R_T/RM is presented ($R_T/RM < 0.6$) (3), the relationship between $\dot{H}_{corr}/\dot{H}_{meas}$ and R_T/RM becomes linear (Fig. 5), which can be described for both types of HFTs by

$$\frac{\dot{H}_{corr}}{\dot{H}_{meas}} = 1.004 + 0.908 \frac{R_T}{RM} \qquad r^2 = 0.999 \qquad (23)$$

Immersion of forearm in water. Table 2 presents the temperature and heat flux data for the last 15 min of 3-

h immersions of the forearm in water at T_w ranging from 15 to 36°C (n = 20). As expected, T_c and T_{sk} of the forearm increase with T_w, but $\dot{H}_{meas}$ from the skin is inversely proportional to T_w. The mean values $\dot{H}_{corr}$ are 9.8 ± 1.6% higher than $\dot{H}_{meas}$ for $T_w \leq 30$°C and 25.3 ± 7.0% higher than $\dot{H}_{meas}$ for $T_w > 30$°C.

DISCUSSION

Because of their convenience, HFTs are being used increasingly to study human thermal physiology under different environmental conditions. However, the vast majority of studies have used the factory calibration data provided with the HFTs, and little attention has been given to the effect of R_T on the true heat flux from the skin. The results of this study indicate that the heat flux indicated by the HFTs must be interpreted with care.

Calibration of HFTs. The recalibrations of HFTs from two companies have shown different degrees of deviation between the factory-supplied and experimentally determined calibration constants. The results indicate that the mean difference (in absolute value) between the experimental calibration constants and the factory constants is 28-fold larger for HFTs *A* (20.2%) than for HFTs *B* (−0.7%). For each HFT *A* calibrated, the factory constant was overestimated, as opposed to the HFTs *B*, for which the factory constants were about equally over- and underestimated.

These results are consistent with the findings of Nuckols and Piantadosi (1), Snellen and Frim (13), and Sowood (14), who found a similar magnitude of error between the manufacturers' calibrations and the experimentally determined calibration for HFTs having similar characteristics to those used in the present study. The advantage of the present study over the others is that the calibration of both types of HFT were performed by the same reliable and reproducible method of calibration over a larger range of thermal flux (0–500 W/m^2), thus making the comparison between the two types of HFTs more accurate.

The differences between the manufacturers' and the experimental values may be due to an underestimation of the heat flux by the manufacturers' method because the transducers were calibrated before waterproofing (9, 14) or because the method did not allow for the insulative properties of the disk material (14). Whatever the cause, this study shows a significant error in the calibration of HFTs provided by manufacturers. Even if the calibration error was greater for one HFT type than for the other, it is advisable to carefully recalibrate the transducers if accurate values of heat flux are required. It is particularly important to recalibrate the transducers if the site of their measurement is weighted heavily in a weighted average such as on the human body.

Correction for the thermal resistance of the HFTs. The study involving the variable-R model indicates clearly that a strong relationship exists between the underlying "tissue" insulation and the relative error in thermal flux due to the thermal resistance of the HFT. For high values of "tissue" insulation ($R_M > 0.5$°C·m^2·W^{-1}, $R_T/R_M < 0.02$; Fig. 5) the measured value of heat flux nearly represents the actual thermal flux from the tissue (<1% error), but for very low values of "tissue" insulation ($R_M < 2 \times 10^{-4}$°C·m^2·W^{-1}, $R_T/R_M > 50$; Fig. 4), an error as high as 500% can be present in the measurement of the thermal flux by an HFT.

To understand this effect, take the example of two systems that involve a "nearly perfect conductor" (i.e., $R_M \ll R_T$) and a "nearly perfect insulator" (i.e., $R_M \gg R_T$). If an HFT is fixed on the conductor, then the HFT becomes the major resistance to the heat transfer through the system at that location. Consequently, heat flux measured at the HFT site ($\dot{H}_{meas}$) will be much less than that through just the conductor, and a correction is necessary.

On the other hand, when a "nearly perfect insulator" is used, the thermal resistance added by the HFT to the system ($R_M + R_T$) is negligible compared with the thermal resistance of just the insulator. Therefore, the heat transfer through the system is virtually the same as that through just the insulator. In that case, the HFT will closely measure the actual value of heat transfer through the insulator. It is therefore evident that the difference between $\dot{H}_{meas}$ and $\dot{H}_{corr}$ is highly dependent on the insulation of the material (or tissue) under the HFT. The deviation from the true value of thermal flux increases with decreasing insulation of the underlying material.

The above interaction becomes particularly important when HFTs are used on highly conductive materials, such as metallic-skin mannequins (copper or aluminum). In that case, because the underlying material insulation value is low ($R_T/R_M > 1.5$; Fig. 4), the values of heat flux read by the HFTs may underestimate the true value of heat flux by >100%, depending on the insulation of the mannequin skin.

From a physiological standpoint, the underestimation of heat flux through the skin measured by an HFT can be important when the device is used during vasodilation in warm subjects, as suggested by Gin et al. (5) and Wissler and Ketch (16). For that situation, as shown in Fig. 5, the underestimation of the measured heat flux can range from 45 to 52% from the true value of heat flux [R_T/R_M between 0.48 and 0.52 (3)] depending on the HFT model used and the degree of vasodilation in the tissue. The Wissler-Ketch (16) equation (*Eq. 17*) must be used to correct the measured heat flux for R_T when the device is used on vasodilated skin. When the correction equations are used, R_T is 0.0104°C·m^2·W^{-1} for the HFTs *A* and 0.0064°C·m^2·W^{-1} for the HFTs *B*. From these values, it is evident that the correction for R_T is more important in the case of the HFTs *A*, because their R_T value is 63% higher than the value for HFTs *B*.

When HFTs are used on vasoconstricted skin in cool subjects [R_T/R_M between 0.025 and 0.15 (3)], the underestimation of the measured heat flux is less important, ranging from 3 to 13%. It is therefore not as important to correct the heat flux values for R_T when the device is used on vasoconstricted skin.

The data presented in Table 2 illustrate the magnitude of error due to R_T that is involved when a recalibrated HFT is used to measure the thermal flux from a human forearm immersed in water at different T_w. At T_w lower than the lower critical temperature in water [~30°C

(10)], the tissues are vasoconstricted after immersion in water (2). The error due to the R_T is only 9.8% when the tissues are vasoconstricted, but it increases to 25.3% at T_w of 36°C, where the tissues are partially vasodilated. These data are in agreement with the results found with the variable-R model. They also support the conclusion that the value of thermal flux measured by an HFT should be corrected for the error due to R_T when the underlying tissues are in a vasodilated state.

The data presented in this study are limited to the conditions for which they were obtained (i.e., HFT fixed on exposed tissue during water immersion) and cannot be used for other types of environments or for clothed subjects. Any condition that changes the insulation value of the environment above the HFT will also change the relationship between the error in flux measurement ($\dot{H}_{corr}/\dot{H}_{meas}$) and the insulation of the underlying tissue. In addition, when the Wissler-Ketch correction equation is used to calculate $\dot{H}_{corr}$, it is important to measure or estimate correctly T_c of the segment where the HFT is fixed. Noninvasive methods such as rectal, esophageal, or oral temperature measurements have been shown by several authors to be invalid to estimate T_c of limbs, particularly during cold stress or at thermal neutrality (unpublished observations; 8) (Table 2). For example, by using the rectal temperature value instead of T_c to calculate $\dot{H}_{corr}$ during the immersion of the forearm in 15°C water, $\dot{H}_{corr}$ would have been equal to 86.4 W/m^2 instead of 90.5 W/m^2, an underestimation of nearly 5%.

The calibrations of two different types of waterproof HFTs have shown significant differences between the recalibration and the manufacturer's constants. Furthermore, a significant difference exists in the error of calibration between the two manufacturers. Therefore, it is important to recalibrate the HFTs if accurate values of heat flux are required.

HFTs inherently underestimate the thermal flux being measured because of the effect of R_T. The variable-R model illustrated that the magnitude of this underestimation increases as the underlying tissue insulation decreases. A physiological condition that minimizes the deviation from the true value of heat flux is a low perfusion rate in the underlying tissue (i.e., vasoconstriction), because the thermal resistance of the tissue increases with decreased perfusion. Another situation that minimizes the importance of correction is the measurement of the heat flux for a dressed subject during exposure to cold air. In this case, the thermal resistance of the clothing and still air layers diminishes the R_T contribution of the HFT. However, the use of HFTs on nude subjects in highly conductive environments such as water and particularly under conditions that do not produce vasoconstriction may cause an underestimation of the heat flux by the transducer of 30–40%. For these particular cases, it is important to correct the measured values of heat flux for the R_T by using, for example, the Wissler-Ketch (16) correction formula (*Eq. 17*). The heat flux data from experimental immersions of the forearm in water at different temperatures by use of the variable-R model illustrated this; the underestimation of the measured heat flux was ~10% during vasoconstriction and ~30% during partial vasodilation of the tissues.

The HFT is a device that represents a compromise between sensitivity and accuracy of measurement. If used properly, it provides useful information within an acceptable range of error. The error in the measurement of the thermal flux should not exceed ~5% when care is taken *1*) to calibrate the HFT and *2*) to correct for R_T.

APPENDIX

Application of the Correction Formulas for Air Exposure

The correction *formulas 12, 14,* and *17* are applicable for air exposure, where radiative heat transfer occurs if the following conditions are met: *1*) the emissivity of the heat flux transducer is close to that for skin, i.e., near unity (both types of HFT in this study satisfied this condition) and *2*) T_u is close to T_{sk} [A 1°C difference between T_u and T_{sk} (maximal difference occurring during cold stress in air) will cause a deviation of <0.1% between the effective thermal resistances of the upper surface of the HFT and the skin ($Reff_u$ and $Reff_{sk}$, respectively).] This is demonstrated as follows. For air exposure, *Eq. 6* becomes

$$\dot{H}_{corr} = \frac{(T_{sk} - T_a)}{R_a} + R_{sk} \qquad (A1)$$

where T_a is the air temperature, R_a is the air resistance, and R_{sk} is the radiative heat transfer from the skin. *Equation A1* can be rearranged such that

$$\dot{H}_{corr} = \frac{(T_{sk} - T_a)}{Reff_{sk}} \qquad (A2)$$

where

$$Reff_{sk} = \frac{R_a}{1 + R_a \cdot h_{rsk}} \qquad (A3)$$

and h_{rsk} is the radiative heat transfer coefficient given by

$$h_{rsk} = \sigma \cdot \epsilon_{sk}(T_{sk} + T_a)(T_{sk}^2 + T_a^2) \qquad (A4)$$

where σ is the Stefan-Boltzmann constant and ϵ_{sk} is the emissivity of skin (12). Similarly, *Eq. 10* becomes

$$\dot{H}_{meas} = \frac{(T_u - T_a)}{Reff_u} \qquad (A5)$$

where

$$Reff_u = \frac{R_a}{1 + R_a \cdot h_{ru}} \qquad (A6)$$

and

$$h_{ru} = \sigma \cdot \epsilon_u(T_u + T_a)(T_u^2 + T_a^2) \qquad (A7)$$

Therefore, if $\epsilon_u \approx \epsilon_{sk}$ and $T_u \approx T_{sk}$, then $Reff_u \approx Reff_{sk}$. Substitution of these values in place of R_a in *Eqs. 6, 7, 10,* and *11* will lead to the correction formulas *Eqs. 12, 14,* and *17*.

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